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ELASTIC STABILITY CONSIDERATIONS FOR DEEP SUBMERGENCE CERAMIC PRESSURE HOUSINGS

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ABSTRACT

This paper discusses stability considerations in the design of ceramic pressure housings to prevent catastrophic failure of the housing under hydrostatic load. Emphasis is on trends discovered in the stability analysis using the program BOSOR4, of cylindrical housings closed on both ends with hemispherical caps. Design of metallic rings for the joining of two or more cylindrical sections is also discussed.

INTRODUCTION

When designing pressure housings for deep submergence use there are several important properties that one looks for in the selection of the material. Ceramic such as alumina is very well suited for use in deep submergence housings because it has very high compressive strength, high Young's Modulus, relatively low density, and excellent corrosion resistance. Furthermore, the price of an alumina ceramic housing, when designed for easy fabrication can be lower than the price of a titanium housing designed for the same service depth, the performance, measured in terms of weight to displacement ratio of the housing will be better than that of titanium.

The design of ceramic pressure housings for deep submergence use requires two types of analysis. The first is stress analysis; which determines whether stresses in the components are below allowable values to prevent material failure.

The second analysis is that of elastic stability. This analysis ensures that the pressure housing does not collapse by buckling under external hydrostatic pressure.

This paper describes the buckling analysis of a simple cylindrical ceramic pressure housing closed on both ends by hemispheres. The analysis was done using BOSOR4, a computer program for stress, stability, and vibration analysis of shells of revolution. A large number of design iterations were made to determine key trends in the design of pressure housings stable enough to withstand pressures at great ocean depths.

BUCKLING CONSIDERATIONS

The variables that affect the buckling behavior of a pressure housing fall into two classes: material properties and geometric properties.

The only material properties that affect buckling are Poisson's ratio and Young's Modulus, E. Poisson's ratio is not very important and does not vary much from material to material. Young's Modulus is very important. It is advantageous in designing for buckling resistance to choose a material with a high E. Alumina ceramic for instance has an E of 44,000,000 psi which is one and one half times that of steel, and three times that of titanium. The important point is that while properties such as compressive strength are important in the design of pressure housings for deep submergence use, it has no affect on the buckling resistance of the housing.

Perhaps more important than the material properties is the geometry of the structure. Round geometries are inherently more stable than rectangular geometries. This is why we do not design square pressure vessels. For long housings the most practical shape is a cylinder. The cylinder should be closed by hemispheres rather than by flat plates because hemispheres resist buckling more efficiently than plates do.

All of the dimensions of a cylinder affect its buckling pressure. The dimensions are length, diameter, and thickness. These are commonly non-dimensionalized into the ratios L/D and t/D. The buckling pressure of cylinders does not depend on the size of the cylinder but rather on these two ratios. A large L/D will lead to lower buckling pressure, small t/D will do the same. When design aides such as BOSOR4 are not available the author recommends the use of the collapse pressure curves developed by R.Von Mises. Experimental data at NRaD shows that the collapse pressures calculated using these curves should be multiplied by about 0.75 for actual results.

For hemispheres, the important geometrical properties are thickness and diameter. Again, a smaller t/D ratio leads to a lower buckling resistance. The formula for the buckling of an ideal sphere is:

$$P = \frac{2 E t^2}{R^2 \, SQRT(3(1-v^2))}$$

It is recommended that this value be multiplied by 0.8 for actual results. As it turns out in the design of cylindrical pressure housings it is the cylinder which is the less buckling resistant portion of the structure. This does not mean that if the cylinder is designed to be buckling resistant, the entire structure can be considered buckling resistant. As a matter of fact, if the cylinder and the hemispheres are individually designed to some buckling pressure, the buckling resistance of the entire structure is ***not*** necessarily equal to that of the weaker part, in fact it usually is lower. A simple analogy to this is that if one designs two columns that are individually resistant to buckling, it does not follow that one can stack them on top of each other and expect the combined structure to be as resistant to buckling as the individual columns.

Cylindrical housings are often made more resistant to buckling by integrating ribs into them. This has a stiffening effect on the cylinder. It allows one to have lower t/D ratios while still maintaining equal buckling resistance, thereby saving substantial amounts of weight. Rib-stiffened cylinders are not discussed in this paper because integral ribs are difficult to incorporate into the design of ceramic cylinders without raising the fabrication cost considerably.

HOUSING MODEL DESCRIPTION

The housing analyzed is a single 18 inch long by 12 inch diameter alumina ceramic cylinder closed on both ends by hemispheres as shown in Figure 1. The baseline design has hemispherical end bells made of alumina ceramic with half the wall thickness of the cylinder. By designing hemispheres with wall thicknesses that are half of the cylinder's the radial deflection under external hydrostatic pressure is matched. This helps prevent large bending moments, in the ceramic at the cylinder-hemisphere interface; these could lead to tensile failure of the ceramic.

In the BOSOR4 model the cylinder was free to rotate at the hemisphere interface. This assumption gives conservative results: when the rotation is fixed the buckling values obtained are only 1 to 2 percent higher.

The material properties used in all the analyses are shown in Table 1. It was assumed in the BOSOR4 model that the cylinders were of ideal geometry. This approximation is fairly realistic since ceramic cylinders can be finish ground to very tight tolerances; cylinder thicknesses to within 1 thousandths of an inch.

With the ratio of the cylinder wall thickness to hemisphere wall thickness fixed at 2.0 , iterations were made using BOSOR4 to determine what wall thickness would yield a buckling pressure of 13,500 psi. This represents a 1.5 safety factor of failure against buckling for operation at depths of 20,000 ft seawater. (1.5 x 9000 = 13,500 psi) . The wall thickness that was finally reached was 0.425 inches in the cylinder and 0.2125 inches in the hemisphere. The membrane stress levels in the cylinder and the hemisphere were found to be acceptable for alumina ceramic (127,000 psi, Safety Factor= 2.4 on compressive strength). This was the baseline housing. Changes to this design were then made to determine the effect on the collapse pressure of the housing.

VARIATIONS IN HEMISPHERE STIFFNESS BY VARYING WALL THICKNESS

Changes were made in the wall thickness of the hemispheres while the thickness of the cylinder wall was kept constant, thereby changing the relative stiffness of the hemispheres to the cylinder. As Figure 2 shows, changing the stiffness of the hemisphere does not affect the overall buckling pressure very much. Doubling the wall thickness of the hemisphere raises the collapse pressure by only 700 psi, that is a 5% increase in buckling collapse pressure for a 100% increase in hemisphere weight. Decreasing the hemisphere stiffness does not result in substantial loss in collapse pressure either.

Closing the cylinder with ends of infinite stiffness results in a buckling collapse pressure of 19,400 psi. Solid flat end plates can be considered to be infinitely stiff.

Flat ends are impractical for actual use for several reasons. First, flats ends need to be extremely thick for both stress and buckling reasons, making them very heavy, the vessel will most likely be a sinker (i.e. W/D > 1.0). Second, it is unlikely that the housing will ever attain the 19,400 psi collapse pressure, instead it will fail at some lower pressure due to the bending stresses introduced into the membrane by the noncompliant ends. If higher buckling resistance is required, this goal is most reasonably attained by increasing the wall thickness of the ceramic cylinder.

Changing the cylinder wall thickness, and therefore its stiffness has drastic effects on the buckling pressure. A 25% increase in cylinder wall thickness (and weight) results in an 81% increase in buckling pressure.

Given the above results it is advisable to let stress dictate the design wall thickness of the hemispheres and then to design the cylinder wall thickness to reach desired buckling collapse pressure. This design method was applied to housings closed with alumina, titanium, and steel hemispheres; results are shown in Table 2.

VARIATIONS IN HEMISPHERE STIFFNESS BY VARYING MODULUS

Variations were made in the Young's Modulus of the hemispheres to determine whether changing the stiffness of the hemisphere by modulus had the same effect on buckling pressure as changing the hemisphere wall thickness. The collapse pressures predicted by BOSOR4 for hemispheres of equal radial stiffness, but modified by different means (i.e. Young's Modulus rather than wall thickness) came out to within 3 percent of each other. Wall thickness seems to have a slightly greater effect on the buckling pressure of the housing. Doubling the hemisphere wall thickness resulted in a 5.3 % increase in buckling pressure while doubling the Young's Modulus increased the buckling pressure by 2.5 %. Figure 3 shows the effect of variations in hemisphere thickness and Young's Modulus on buckling pressure. Note that reduction of the hemisphere thickness leads to a sudden drop in buckling pressure at a stiffness ratio of around 0.5 while reduction in E does not.

A few BOSOR4 calculations were made to determine whether the hemisphere material could be easily substituted without affecting the collapse pressure of the housing. It was found that if the thickness is scaled properly, then hemispheres of different materials could be substituted for the alumina ceramic hemispheres with no change in the buckling pressure of the housing.

Two approaches were tried. The first was to scale the wall thickness of the hemispheres based on matching the radial stiffness of the hemispheres made of different material. The formula that results for this method is :

$$t_f = \frac{E_o\ (1-v_f)\ t_o}{E_f\ (1-v_o)}$$

where

v = Poisson's ratio
E = Young's Modulus

and the subscripts o and f denote original and final material, respectively.

The second method involves scaling the wall thickness to match the buckling pressure of the hemispheres to each other:

$$t_f^2 = \frac{E_o \, SQRT(1-v_f^2) \, t_o^2}{E_f \, SQRT(1-v_o^2)}$$

Calculations show that in substituting titanium, steel, and aluminum for alumina ceramic, consistently higher buckling pressures are attained by use of the first equation while lower values are attained when the second equation is used. All values are within 5% of the original collapse pressure. The author advises using the first equation when substituting hemispheres of different materials for two reasons. First, this equation gives more conservative results. Second, the radial stiffness is matched, and therefore the impact on the stress distribution in the ceramic cylinder should not be affected. Note that any design thickness calculated by these equations should be checked for stress (i.e. can the material tolerate the stress levels that result with this wall thickness ?)

CENTRAL JOINT STUDIES

Often it is desirable to have housings that are of larger size. For hydrodynamic reasons it is preferable to increase the length of a housing rather than the diameter.

When the length of a housing is increased one runs into some problems.

The L/D ratio of the housing has been increased and therefore the wall thickness must be increased to maintain the same collapse pressure.

Long cylinders are more difficult to manufacture out of ceramic. The size of ceramic cylinders is limited by the size of the kiln they are fired in and by the amount of self weight a cylinder can tolerate in its unfired state. When a cylinder is still in its unfired state it is considered to be "soft" and will therefore deform due to its self weight.

For these reasons it is desirable to be able to join two ceramic cylinders by some means, thereby creating a longer housing. There are two methods of joining ceramic sections, these are: brazing, and joining by metallic joint.

Brazing requires that the wall thickness of the individual cylinders be that of a cylinder of length equal to the final configuration. Research at NRaD on 6 inch diameter ceramic cylinders has shown that sections of cylinder when brazed to form one large cylinder do act like one long cylinder.

NRaD also has experience in joining cylinders with metallic joints. Cylinders that are joined by means of a metallic joint are typically designed to individually buckle at the desired service pressure and are then joined with a joint of sufficient buckling resistance to increase the collapse pressure of the entire housing to that required for service. The buckling resistance of a ring is directly proportional to its Young's Modulus and moment of inertia, and is inversely proportional to the cube of the radius.

Two ceramic cylinders of equal design to the baseline design were joined in a model by a one inch wide alumina joint and closed by the baseline design hemispheres. The intent of this study was to determine whether a central joint of sufficient buckling resistance could be designed to attain a buckling pressure of 13,500 psi for the new, longer housing. The joint cross-section was a simple rectangle; its height (outer radius minus inner radius) was increased until the buckling pressure of 13,500 psi was reached.

The resulting joint had a moment of inertia that was 52 times the moment of inertia of a one inch section of cylinder wall. The author makes no generalization or rule based on this result because the answer is dependent on the length to diameter ratio and the thickness to diameter ratios of the cylinders.

SUBSTITUTION OF JOINT MATERIAL

Buckling analysis was done to determine whether the joint material could be substituted without affecting the buckling pressure of the housing. The finding was that as long as the product of E (Young's Modulus) and I (Moment of Inertia) remained constant from one material to the other, the buckling pressure remained within 1 % of the original buckling pressure. This was only shown to be true when the shape of the joint was kept constant.

SUMMARY

In summary the following can be said about the design for buckling resistant housings for deep submergence use:

1. Hemisphere stiffness does not greatly affect the buckling pressure of the housing. Therefore the author advises designing the hemispheres to stress criteria and then varying the cylinder wall thickness until the desired buckling resistance is achieved.

2. The buckling curves by R. Von Mises are useful for preliminary sizing of cylinders. Experience shows that for ceramic the values calculated by these curves should be multiplied by 0.75 for actual results.

3. Changing the hemisphere stiffness by means of the wall thickness or the Young's Modulus is almost irrelevant but differences do exist.

4. Hemisphere materials can be substituted without changing the collapse pressure of the housing if radial stiffness is used for purposes of scaling wall thickness.

5. Central joints of sufficient buckling resistance can be designed to maintain constant buckling pressure while doubling the length of the pressure housing by joining two identical cylinders end to end.

6. Joint material can be changed provided the product of E and I remains constant and the basic shape of the joint remains the same.

CONCLUSION

Further studies are required to determine what moment of inertia is required in the joint or joints between ceramic cylinders to prevent the cylindrical housing from buckling. If a relation is found between t/D, L/D, and load, a useful design guideline could be devised for design of joints in ceramic housings for deep submergence use.

REFERENCES

David Bushnell, "BOSOR4: Program for Stress, Buckling, and Vibration of Complex Shells of Revolution" Lockheed Missiles & Space Co., Inc.

J.D Stachiw, "Exploratory Evaluation of Alumina Ceramic Housings for Deep Submergence Service", NOSC TR 1355, 1990, Naval Ocean Systems Center, San Diego, CA.

Roark and Young, "Formulas for Stress and Strain", McGraw-Hill Inc. 1975

R. Von Mises, "The Critical External Pressure of Cylindrical Tubes Under Uniform Radial and Axial Load", United States Experimental Model Basin.

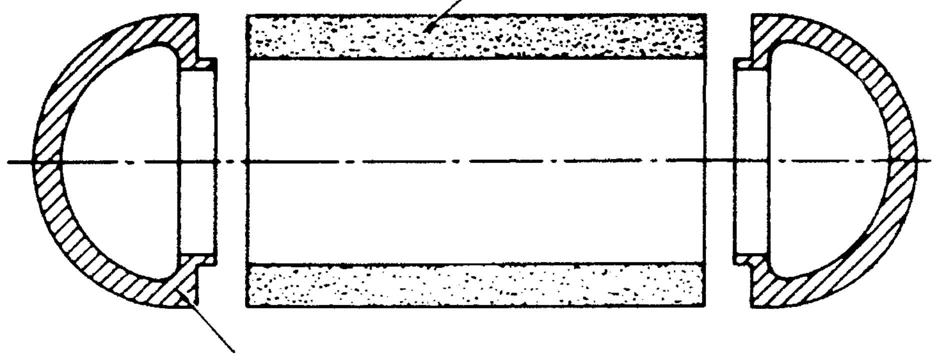

FIGURE 1. CYLINDRICAL CERAMIC PRESSURE HOUSING CLOSED WITH HEMISPHERICAL END BELLS

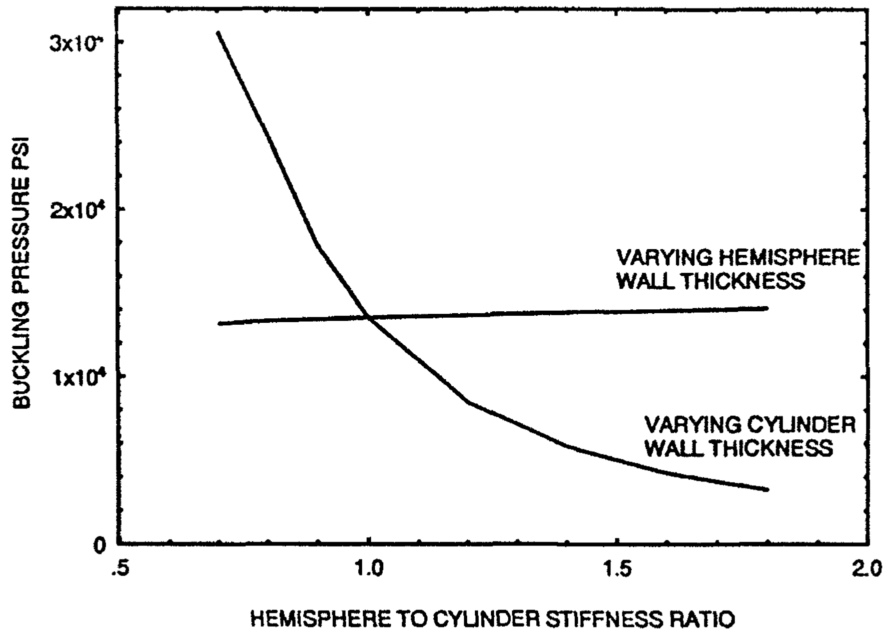

FIGURE 2. EFFECT OF VARYING HEMISPHERE AND CYLINDER WALL THICKNESS ON BUCKLING PRESSURE

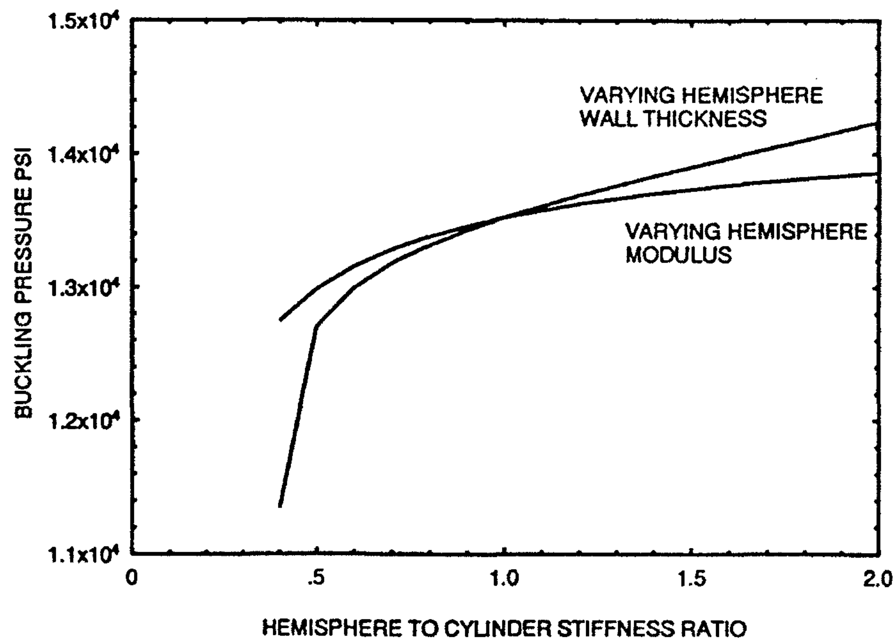

FIGURE 3. EFFECT OF VARYING HEMISPHERE WALL THICKNESS AND MODULUS ON BUCKLING PRESSURE

TABLE 1. MATERIAL PROPERTIES

Material	Young's Modulus (psi)	Poisson's Ratio	Compressive Strength (psi)	Material Density (lbs/cu.in.)
Alumina Ceramic	44,000,000	0.21	300,000	0.13
Titanium 6Al-4V	16,400,000	0.31	125,000	0.16
Steel HY130	29,000,000	0.28	130,000	0.31
Aluminum 7075-T6	10,000,000	0.30	73,000	0.10

TABLE 2. WEIGHT TO DISPLACEMENT RATIOS OF ALUMINA CERAMIC CYLINDERS WITH L/D=1.5 CLOSED BY HEMISPHERES MADE OF VARIOUS MATERIALS*

Hemisphere Material	Design Stress** (psi)	Wall Thickness		Housing W/D
		Hemisphere (in.)	Cylinder*** (in.)	
Alumina Ceramic	150,000	0.18	0.427	0.42
Titanium 6Al-4V	100,000	0.27	0.432	0.49
Steel HY130	104,000	0.26	0.425	0.64

*Designed for 20,000 ft service depth.
**Design stress for hemisphere.
***Cylinder made of alumina ceramic